Bioresource Technology 101 (2010) 2443–2449

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Performance of a Flameless combustion furnace using biogas and natural gas

A.F. Colorado *, B.A. Herrera, A.A. Amell

Science and Technology of Gases and Rational Use of Energy Group, Faculty of Engineering, University of Antioquia, Calle 67 No. 53-108 Bloque 20-435, Medellín, Colombia

ARTICLE INFO

Article history:
Received 5 August 2009
Received in revised form 30 October 2009
Accepted 2 November 2009
Available online 26 November 2009

Keywords:
Biogas
Low calorific value fuel
Flameless combustion
Furnace performance

ABSTRACT

Flameless combustion technology has proved to be flexible regarding the utilization of conventional fuels. This flexibility is associated with the main characteristic of the combustion regime, which is the mixing of the reactants above the autoignition temperature of the fuel. Flameless combustion advantages when using conventional fuels are a proven fact. However, it is necessary to assess thermal equipments performance when utilizing bio-fuels, which usually are obtained from biomass gasification and the excreta of animals in bio-digesters. The effect of using biogas on the performance of an experimental furnace equipped with a self-regenerative Flameless burner is reported in this paper. All the results were compared to the performance of the system fueled with natural gas. Results showed that temperature field and uniformity are similar for both fuels; although biogas temperatures were slightly lower due to the larger amount of inert gases (CO_2) in its composition that cool down the reactions. Species patterns and pollutant emissions showed similar trends and values for both fuels, and the energy balance for biogas showed a minor reduction of the efficiency of the furnace; this confirms that Flameless combustion is highly flexible to burn conventional and diluted fuels. Important modifications on the burner were not necessary to run the system using biogas. Additionally, in order to highlight the advantages of the Flameless combustion regime, some comparisons of the burner performance working in Flameless mode and working in conventional mode are presented.

1. Introduction

Currently, fuels derived from biomass, also known as bio-fuels seem an alternative solution to the future fossil fuel shortage, and for many countries they are a good possibility to produce energy from their own renewable resources. That is why bio-fuels consumption is considered to grow steadily within the next years as a way to achieve a sustainable energy. Usually, this kind of fuels is called low calorific value fuels (LCV), due to the large proportion of inert components in their composition that lower their heating value. For that reason, they present some combustion difficulties related to their stability when they are burned in conventional burners, and there is a lack of appropriate technology to burn them efficiently.

Flameless oxidation (Wünning and Wünning, 1997) or Mild combustion (Cavaliere and Joannon, 2004) is a technology that emits very low pollutant emissions, especially thermal NO_x and CO are lowered to residual values, while maintaining a high thermal performance of the system. Under the special conditions of the combustion regime the reactions take place in a volume sustained by the hot medium above the self-ignition temperature, and it is not possible to observe any visible flame or luminous effect; that is why the regime was named "Flameless oxidation". The opposite case occurs in conventional combustion systems where reactions are concentrated in a narrow flame front. An important advantage of burners that operate under the Flameless regime is their ability to burn fuels of changing and fluctuating quality, or LCV fuels.

The feasibility of Flameless technology for LCV gases and liquids has been investigated in detail within the European R&D project BIO-PRO (Berger et al., 2006). Recently there is a growing enthusiasm to study the Flameless regime using biomass derived fuels, and some researchers have focused their attention on the phenomenological characteristics of burning LCV fuels under Mild combustion conditions (Dally et al., 2004; Effuggi et al., 2008; Mörtberg et al., 2006). Many publications and technological developments have been evaluated using the most common fossil fuels as liquefied petroleum gas (LPG) and natural gas (NG) (Gupta, 2004; Tsuji et al., 2003; Weber et al., 2005). However, there are not many studies that assess the performance of industrial systems when they are fueled with bio-fuels (Kalisz et al., 2008; Kawai et al., 2002).

One of the main characteristics of a Flameless combustion system is the high exhaust gas recirculation (EGR), which lowers the oxygen concentration and the temperature in the reaction zone, and as a result thermal NO_x is suppressed. Another characteristic is the heat recirculation that is used to recover energy from the combustion products at high temperatures. This energy is then

* Corresponding author. Tel.: +57 3103472376.
E-mail address: andresc380@gmail.com (A.F. Colorado).

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doi:10.1016/j.biortech.2009.11.003

used to raise the temperature of the air stream, and in that way the efficiency of the combustion system is drastically increased. Finally, fuel and oxidant are injected separately at high speed into the combustion chamber, that is the manner to achieve the recirculation patterns and thus the exhaust gas recirculation that reduces the oxygen concentration of the reactive mixture in the combustion chamber well below 15% (by volume).

This paper reports the effect of varying the fuel composition on the performance of an experimental furnace equipped with a self-regenerative Flameless burner. Thermal input and average wall temperature were held constant during the experiments. In order to accomplish this, the heat load was varied to explore how fuel composition affects the productivity in a given process. Two fuels of different compositions were evaluated, biogas (60% CH_4, 40% CO_2) and natural gas ($\sim$97% CH_4); the composition of both fuels is given in volumetric percent. Also, in order to highlight the advantages of the Flameless combustion regime some comparisons of the burner performance working in Flameless and working in conventional mode are presented. These results show a comparison of the temperature profiles along the same positions in the combustion chamber. The uniformity of the thermal field inside the furnace for both fuels is evaluated using a temperature uniformity ratio R_{tu}. Also, the species patterns, pollutant emissions and energy balance for both fuels are presented. Finally, the energy balance was used to calculate the efficiency of the system when it was fueled with biogas and natural gas under the Flameless mode and with natural gas in the conventional mode.

2. Methods

2.1. Experimental facility

An experimental furnace equipped with a self-regenerative burner was used. Four parallel stainless steel tubes with an external diameter of 6.03 cm are located inside the furnace to remove heat from the combustion chamber; these tubes work as a counter-flow heat exchanger that uses a variable mass flow of air. This heat exchanger allows the variation of the thermal load inside the furnace, thus the control of the temperature inside the chamber. One rectangular chimney to evacuate the exhaust gases is located upside the furnace body; the section of the chimney can be modified with a modular damper to restrict the fumes flow. Ideally 100% of the combustion products should be evacuated through the regenerative system, and 0% through the chimney, however, the high suction pressure that is necessary to reach this condition may cause cold air infiltrations into the combustion chamber, as a result the furnace can be cooled down and the process efficiency would be lowered. The walls of the furnace consist of three layers: the external layer is a plate of stainless steel, the second one is a blanket made of ceramic fiber, and finally ceramic fiber blocks cover the inner surface of the combustion chamber. The thermal conductivity of the ceramic fiber is 0.32 W/mK at 1000 °C. An isometric view of the combustion chamber is presented in Fig. 1.

2.2. Burner

For experimental investigations, a burner designed to operate under turbulent diffusion flame mode and Flameless mode was tested. In flame mode, the burner was fueled with natural gas and operated at 50 kW. This operational mode is used just to heat the furnace walls over the autoignition temperature of the fuel, after that, the burner switches to Flameless mode as soon as possible. During the flame mode or conventional mode, 100% of the exhaust gases are evacuated through the chimney, and the regenerative system is not used, therefore the efficiency of the system is lower when compared to the system running on Flameless mode. Additional experiments were carried out in conventional mode (at 20 kW) with the burner fueled with natural gas and an excess of air of 20% (vol.); these experiments were made in order

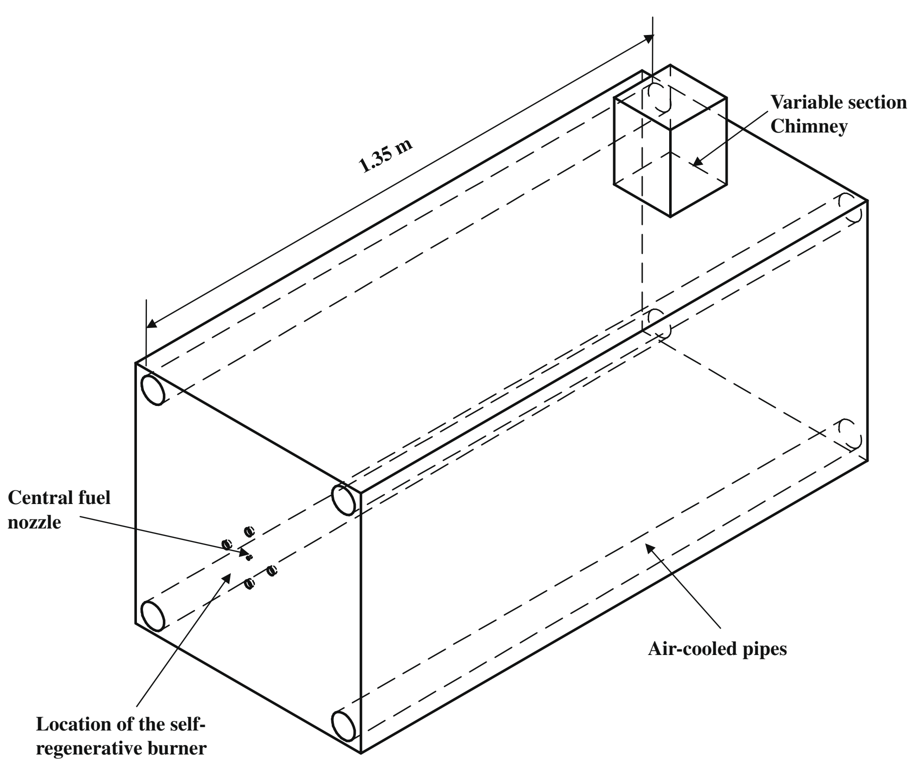

Fig. 1. Schematic view of the combustion chamber.

to highlight some of the advantages of Flameless combustion mode in relation to the flame mode.

For the operation in Flameless mode the fuel nozzle can be interchanged to operate on natural gas, biogas, LPG or synthesis gas. The Flameless burner is equipped with honeycomb regenerators made of cordierite. The honeycombs recuperate energy from the hot exhaust gases to preheat the combustion air; this recuperation technique is part of the heat recirculation process that is used to increase the efficiency of the furnace. The burner injects fuel through a central nozzle and uses four nozzles to extract the combustion products and to inject the combustion air; these four nozzles work in pairs and are located around the central nozzle. To complete the regenerative heat exchange during the Flameless operation mode, the air is injected at high velocity into the combustion chamber through a pair of nozzles; meanwhile, the other two nozzles extract exhaust gases from the combustion chamber preheating the regenerators. The burner injects air and extracts gases through the same nozzles during a period of 30 s (switching time). After that the air nozzles switch to extraction mode and the extraction nozzles switch to air injection mode. During this cyclic process, the fuel continuously flows through the central nozzle.

2.3. Recirculation factor and stability limits

It has been pointed out that there are stability limits for the Flameless combustion regime (Effuggi et al., 2008), and they are dependent on the fuel type, the temperature of the reactive mixture and the recirculation factor (K_v); the last one is the ratio between the mass flow of exhaust gases recirculated ($\dot{m}_r$) and the mass flow of air and fuel ($\dot{m}_a + \dot{m}_F$) ($K_v = \frac{\dot{m}_r}{\dot{m}_a + \dot{m}_F}$). For instance, in a system fueled with CH_4, if the recirculation factor is held between 0 and 3 ($0 < K_v < 3$) while keeping the temperature in the combustion chamber above the autoignition temperature, conventional flames would appear in the combustion chamber. In contrast, when K_v is between 3 and 4.5, a transition regime from conventional flames to Flameless combustion is observed, which is evidenced for a limited peak of CO emissions. Once K_v exceeds 4.5, the Flameless combustion regime is achieved and a strong decrease of thermal NO_x formation occurs. On the other hand, when K_v is >10 an unstable region of the Flameless regime appears, again a high peak of CO emissions is released whilst thermal NO_x remain very low. This instability is caused by the high amount of inert gases that lowers the O_2 concentration cooling down the reaction zone; as a result the concentration of OH radicals is lowered, the reaction rate is slowed down, and therefore the conversion of CO into CO_2 is inhibited. According to the same study, for a biogas (50% CH_4, 50% N_2 by volume) a $K_v < 3$ and $K_v > 7.3$ it is enough to reach the unstable region. A proper selection of K_v for both fuels must lead to a steady and highly clean combustion.

During the Flameless mode, the burner was tested at 20 kW on natural gas with a 3.2 mm fuel nozzle diameter. For biogas a fuel nozzle of 5.4 mm diameter was used at the same thermal input (20 kW). The fuel nozzles diameters were selected according to the Strong Jet Weak Jet (SJWJ) theory (Grandmaison et al., 1998; Sobiesiak et al., 1998). This theory made possible to select a proper diameter of the fuel nozzle to obtain a proper recirculation factor (K_v) to obtain Flameless combustion regime between the stability limits for both fuels.

2.4. Experimental conditions

In Flameless mode, the burner was fueled with biogas and natural gas at a thermal input of 20 kW. An excess of air of 20% (volumetric) was used, it was calculated using the air and gas flow rates that entered into the combustion chamber and was confirmed with the flue composition of CO_2 and O_2 at the chimney. During Flameless operation with natural gas and biogas 85% and 74% of the total flue gas flow rate was extracted through the regenerators, respectively; while the remainder 15% and 26% was exhausted through the main chimney. A process at 850 °C was simulated during the experiments. Average temperature of the walls was held over 870 °C to ensure the self-ignition of biogas and natural gas. The air combustion was preheated at 680 °C during the operation with biogas and 537 °C with natural gas. A scheme of the experimental setup is shown in Fig. 2.

The following variables were measured during the tests:

- Temperature field along three axes in a horizontal plane located at the middle of the furnace height (midplane). This field was measured using a K type (Ni–Cr) thermocouple of 1 mm diameter wire.
- Dry basis species fields along three axes in the midplane of the combustion chamber using a cooled insertion probe.
- The inner roof wall temperature; all the thermocouples are mounted flush of the insulation.
- Flow rates of combustion air, biogas, natural gas, cooling air, exhaust gases through the regenerators and exhaust gases through the chimney. The flow rates were measured with mass flow meters based on the hot wire principle. Also, temperatures and pressures were measured for each flow.
- Analysis of the species (O_2, CH_4, CO_2, CO and NO_x on a dry basis) at the chimney and exhaust gases passing through the regenerators. A non-dispersive infrared (NDIR) sensor was used for determining CH_4, CO_2 and CO concentration. O_2 measurements were carried out with a sensor that uses the paramagnetic principle. NO_x emissions were measured using the chemiluminescence technique. The accuracy of the analyzer is ±1 digit, which is equivalent to 1 ppm of NO_x or CO and 0.01% of O_2 or CO_2.

3. Results and discussion

3.1. Temperature fields

Fig. 3 shows the measured temperature profiles along the central axis of the combustion chamber; the figure gathers the temperatures profiles of the system burning natural gas and biogas in Flameless operation, and when burning natural gas in conventional mode. The temperature profiles along the right and left axis are not shown due to their similarity with the central axis profile (in Flameless mode).

In Flameless mode, when the burner was fueled with biogas a slight reduction of the temperature field was observed; for NG the average temperature in the midplane of the combustion chamber was 953 °C, while for biogas it was 907 °C this temperature reduction was equivalent to 4.8% less in relation to temperature of the chamber when the burner was fueled with natural gas. The increased amount of inert gases flowing in the combustion chamber cools down the reactions lowering the temperature of the chamber. When burning biogas the excess of fumes corresponds to the mass fraction of CO_2 in the biogas, which increases the amount of fumes by 8.5% (mass fraction) when compared to the total amount of fumes produced with natural gas. Also, the CO_2 has a superior cooling effect than N_2 due to its higher heat capacity (C_p) at high temperatures (C_{pCO_2}/C_{pN_2} = 1.28/1.20 at 1200 K) and its enhanced radiation properties allows it to absorb more radiation from the reaction zone. This condition leads to a temperature reduction of the furnace walls, which is in agreement with the studies conducted by other researchers (Dally et al., 2004; Szegö et al., 2009). It is noteworthy that this result is promising for the sake of the use of alternative fuels under the Flameless combustion regime. According to this result, a furnace could burn bio-

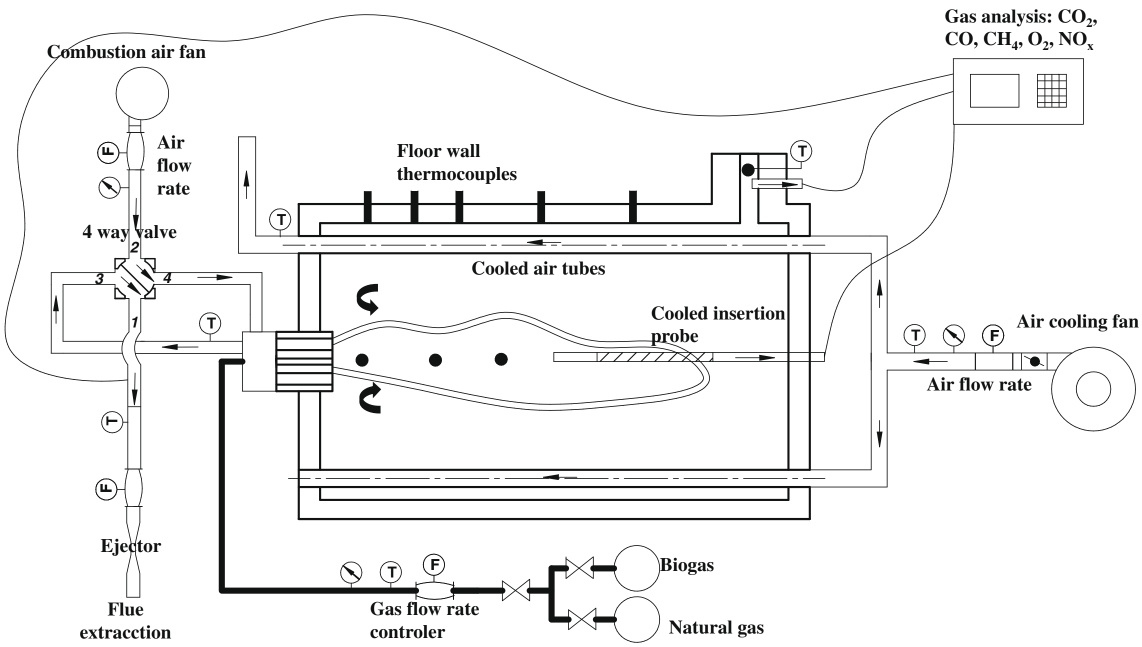

Fig. 2. Experimental setup.

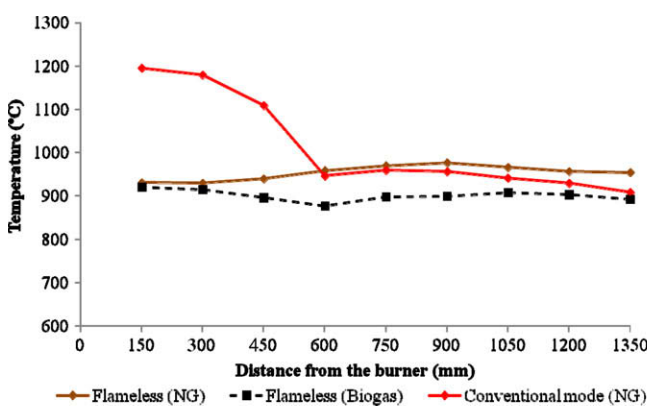

Fig. 3. Temperature profiles along the central axis (Flameless mode fueled with biogas and NG, and conventional mode fueled with NG).

gas instead of natural gas and the temperature field inside the chamber would not be affected considerably.

During Flameless mode a very uniform and flat temperature profile was found for both fuels. Conversely, in conventional mode with natural gas a temperature peak was found in the near field of the burner. To assess the temperature uniformity of gases inside the furnace, a temperature uniformity ratio (R_{tu}) as defined by (Yang and Wlodzimierz, 2006) was used for every case. This ratio is defined as follows:

$$R_{tu} = \sqrt{\sum\left(\frac{T_i - \bar{T}}{\bar{T}}\right)^2}$$

where T_i (K) represents the temperature measured in every point of the chamber, and $\bar{T}$ is the average temperature. If the difference between T_i and $\bar{T}$ in every point of the combustion chamber is very small the R_{tu} tends to zero. To evaluate the R_{tu} all the temperatures measured in the midplane where used (not shown). During Flameless operation, the R_{tu} for natural gas was 0.08 (which is equivalent to a standard deviation of 10.14 °C), whereas for biogas it was 0.057 (or a standard deviation 16.65 °C), this means that a more uniform temperature field in the case for biogas was achieved. In contrast to the highly uniform field found for the Flameless combustion mode, in conventional mode, the R_{tu} was 0.37 (standard deviation 113.91 °C).

Analyzing both fuels under the Flameless combustion it was observed that the Reynolds number of the central jet (fuel) was turbulent (Re_{NG} = 15,373 and Re_{biogas} = 21,227) and the air stream velocity was held constant around 79 m/s (Re_{air} = 23,414). Although the biogas viscosity is higher and its injection velocity is lower (V_{biogas} = 54 m/s) when compared to NG (V_{NG} = 81 m/s), the Reynolds number for biogas remains higher due to its higher density and the larger flow rate required to achieve the same thermal input, thus the higher uniformity regarding the biogas is related to the improved mixing patterns that occur as a consequence of the higher turbulence. Besides, the larger amount combustion products that recirculate the chamber, especially CO_2 and its enhanced radiation properties lead to a better distribution of the heat throughout the combustion chamber.

3.2. Species profiles

The species concentration along the central axis (collinear to the fuel nozzle) in the combustion chamber was measured using a water cooled insertion probe. This device is designed to suddenly stop the reactions by a rapid cooling of the reactants. The insertion probe has a reach of 600 mm (it covers the second half of the combustion chamber), and it is inserted into the combustion chamber from the opposite wall to the burner. The analyzed species were CO, CO_2, O_2 and CH_4. Figs. 4a and 4b show CO and CH_4 profiles along the central axis of the combustion chamber, respectively. These figures compare the species patterns of the burner fueled with NG in conventional mode, and fueled with biogas and natural gas in Flameless mode. In conventional mode the concentration of CO measured in the second half of the combustion chamber along the central axis remained below 40 ppm, while CH_4 concentration was always 0%. This result indicates that the complete oxidation of the fuel occurs in the zone close to the burner. On the other hand, when the system worked under the Flameless regime a similar

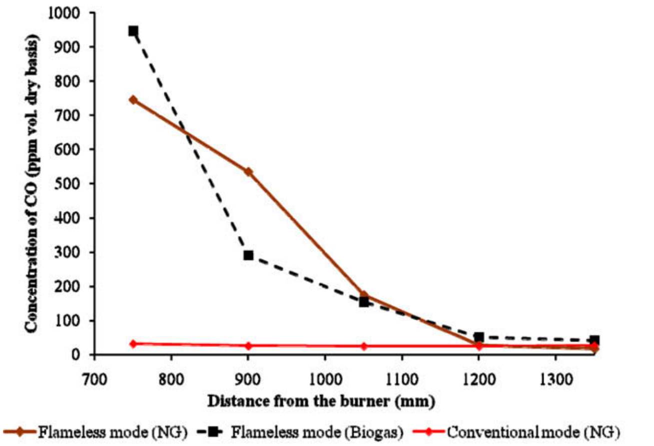

Fig. 4a. CO profile along the second half of the combustion chamber (Flameless mode fueled with biogas and NG, and conventional mode fueled with NG).

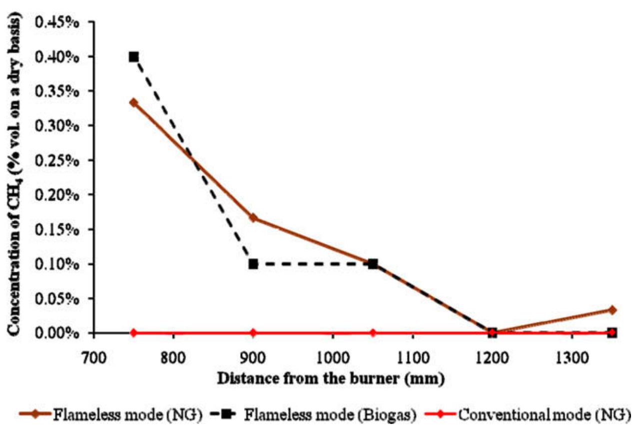

Fig. 4b. CH_4 profile along the second half of the combustion chamber (Flameless mode fueled with biogas and NG, and conventional mode fueled with NG).

trend was observed for both fuels; a peak of CO and CH_4 was measured at 750 mm from the fuel nozzle. Then, when the distance from the burner increases, the CO and CH_4 concentration for both fuels decreases gradually to residual values (below 40 ppm of CO and 0.05% of CH_4 at 1350 mm from the burner). These results show that the region of active reactions is much longer in Flameless regime; in fact the oxidation reactions cover the complete length of the chamber. The complete oxidation of CO and CH_4 in Flameless mode is achieved due to the high turbulence, the strong recirculation patterns that increase the residence time of the fuel, the high temperature of the recirculated exhaust gases above the autoignition temperature and the uniform availability of oxygen throughout the furnace.

Fig. 4c shows the volumetric concentration of CO_2 and O_2 along the central axis of the combustion chamber. In this case the burner was fueled with biogas and natural gas in Flameless combustion mode. It is noteworthy that oxygen distribution along the second half of the combustion chamber was highly uniform and the trend was flat for both fuels analyzed. The oxygen concentration remained around 3.7% for both fuels. The low O_2 concentration and the flat temperature field over the self-ignition temperature guaranteed the fundamental conditions of the Flameless combustion regime. Regarding the CO_2 distribution, a higher CO_2 concentration was found with biogas; it corresponds to the additional amount of CO_2 in the fuel composition. In terms of combustion analysis, when burning pure methane with an excess of air of 20%, the maximum

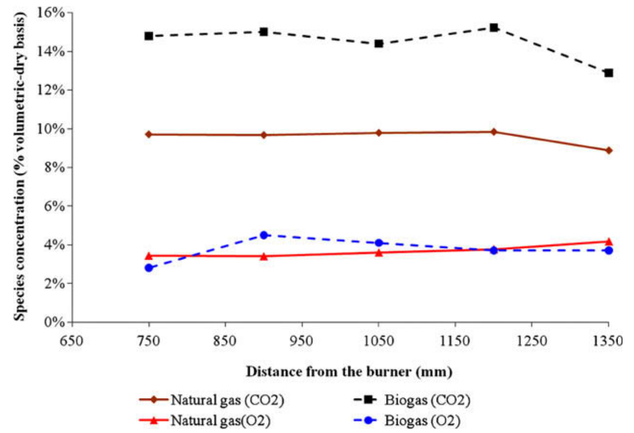

Fig. 4c. CO_2 and O_2 profile along the second half of the combustion chamber (Flameless mode).

concentration of CO_2 in the fumes would be 11.3% (vol. on a dry basis); whereas to burn biogas with the same excess of air, the CO_2 concentration in the fumes would be 15% (vol. on a dry basis). The highly uniform concentration of O_2 and CO_2 measured along the combustion chamber indicate an excellent mixing of the exhaust gases with the fresh reactants throughout the combustion chamber.

3.3. Emissions

The average concentration of pollutant emissions are shown in Fig. 5. Pollutant emissions were very low and similar during Flameless operation with both fuels; only residual values of NO_x and CO were measured at the chimney. These results indicate that under Flameless combustion regime, in a furnace environment, the dilution of methane with inert gases such as CO_2 by 40% (volumetric) has a negligible effect on pollutant emissions. To accomplish this, just the fuel nozzle diameter was modified in order to hold constant the recirculation factor. Although it was not possible to measure the recirculation factor (K_v), the low NO_x and CO emissions, the very uniform temperature profiles, and the visual characteristics of the reaction volume were in agreement with those reported for Flameless combustion within the stable range (Effuggi et al., 2008).

Also, it has been pointed out by Szegö et al. (2009) that the highly diluted conditions of the Flameless regime are more prone

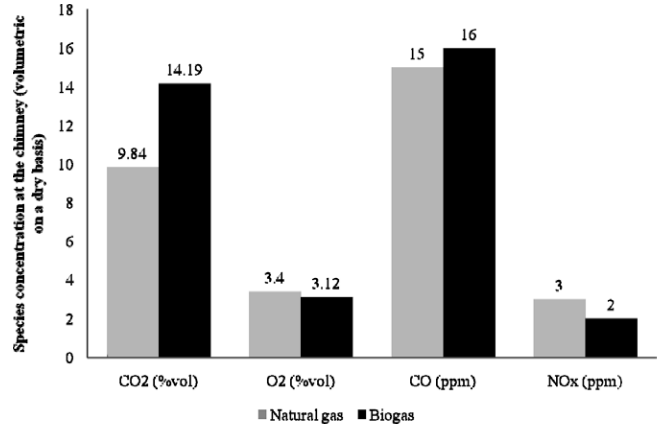

Fig. 5. CO_2, O_2, CO and NO_x emissions at the chimney (Flameless mode).

to CO emissions than conventional flames given the reduced concentration of hydroxyl radical (OH), which controls the conversion of CO into CO_2. This is based on some measurements carried out by (Medwell et al. (2007, 2008)) that showed that OH concentration was lower when the volumetric concentration of oxygen in the oxidant was reduced from 9% to 3% on a dry basis; a lower concentration of O_2 may be assumed as a higher K_v. Although the lower concentration of OH could maximize the CO emissions, the longer residence time in a furnace environment under the Flameless regime eases the complete conversion of CO into CO_2 for either fuel pure or diluted. Additionally, it has been identified that fuel dilution with inert gases leads to a reduction of NO_x emissions given the cooling effect of inert gases that lowers the temperature of the reaction zone (Dally et al., 2004). Even thought, since the temperature profiles in the furnace were held around the same level, the NO_x emissions measured were practically the same. Additionally, the highly uniform thermal field and the temperatures in the furnace below 1000 °C guaranteed the ultra low NO_x emissions produced.

3.4. Energy balance

Table 1 shows a summary of the energy balance made on the furnace during the operation in Flameless mode with NG and biogas, and the conventional mode with natural gas. The thermal input takes into account the amount of energy that enters into the combustion chamber with the fuel, the air that enters into the system through the cooling tubes, and the combustion air that enters into the combustion chamber before it is preheated by the regenerative honeycombs. The thermal energy input was held constant around 21 kW for NG and biogas and both operational modes. The heat leaving the furnace through the walls was estimated after measuring the temperature of the outer walls and using an approach for natural convection, and radiation of the vertical and horizontal walls. This heat loss was around 3 kW in all cases (~14% of the overall energy). The amount of energy removed by the air-cooled tubes was calculated using the temperature and mass flow rates measurements of the air entering and leaving the cooling tubes; this energy output accounts 68% for biogas and 70% for natural gas. This implies that negligible differences when using a lower calorific value fuel occur under the Flameless combustion regime, thus productivity would not be drastically altered when burning biogas instead of NG in a furnace in Flameless mode. On the other hand, in conventional mode only 41.4% of the energy was removed from the chamber through the cooling tubes (efficiency). This reduced efficiency is the consequence of evacuating 100% of the combustion products (at 808 °C) through the main chimney, instead of using the regenerative system to recover energy. The energy losses with the hot combustion products through the chimney account 39.2% of the total energy input.

When the system was fueled with biogas in Flameless mode, the energy loss with the hot combustion products (at 851 °C) through the chimney, which are 26% of the total fumes produced, were estimated as 12.9% of the total energy input. When the system was fueled with natural gas in Flameless mode, 15% of the combustion products (at 881 °C) were evacuated through the chimney and the energy losses through the chimney were only 6.5% of the total energy input. The higher energy losses through the chimney when the system was fueled with biogas are related to the higher concentration of CO_2, which has a higher radiation heat absorption capability allowing it to retain more heat from the reaction zone. Besides, as CO_2 is denser and its heat capacity is higher at high temperatures than other diluting gases as N_2, it enhances its ability to catch heat from the reaction zone. Therefore, there is a higher amount of energy in the biogas fumes when compared to the NG fumes. As the biogas combustion products that flow through the regenerator contain a higher amount of energy than those of natural gas combustion; a higher efficiency of the regenerative system is achieved. The estimated regenerative efficiency when the burner was fueled with biogas was 85%, while for natural gas it was 66%, which explains the feasibility to accomplish a similar global efficiency for both types of fuel under the Flameless combustion regime.

Table 1
Energy balance.

Combustion mode (fuel)	Flameless mode (biogas)	Flameless mode (natural gas)	Conventional mode (natural gas)
Energy input (including fuel + combustion air + cooling air) (kW)	21.13	21.31	21.02
Energy losses through the wall (kW)	3.00	3.07	3.2
Energy removed by the cooling tubes (kW)	14.39	14.99	8.71
Energy output through the chimney (kW)	2.72	1.39	8.25
Energy of the combustion products after the regenerative system (kW)	1.01	1.36	0
Efficiency (%)	68	70	41.4

4. Conclusions

Under the Flameless combustion regime the performance of a furnace remained practically constant when burning natural gas or biogas. In both cases, NO_x and CO emissions were very low, lower than 3 ppm and 16 ppm, respectively. When the system was fueled with biogas the efficiency was 2% lower, and a minor reduction of the temperature field was found. Therefore, the thermal load of the Flameless system could be held constant while utilizing biogas instead of natural gas. These results indicate that the Flameless combustion regime eases the interchangeability between fuels of different compositions.

When the burner was fueled with biogas compared to the burner fueled with natural gas (in Flameless mode), the energy losses through the chimney were higher; even thought a higher efficiency of the regenerative system was achieved. It was found that for the same amount of gases passing through the regenerative system, the biogas combustion products have a higher concentration of CO_2, which has better radiation properties, higher absorption capability, and a higher heat capacity. These characteristics improve the heat exchange between the flue gases and the honeycombs regenerators.

According to the CO and CH_4 profiles measured along the second half of the furnace (in Flameless mode), the reaction zone is distributed along the complete length of the chamber and a similar trend was identified for either kind of fuel. This was related to the similar oxygen availability and the uniform temperature field along the furnace that guaranteed a similar species pattern.

The Flameless combustion mode showed several advantages in relation to the conventional mode; a longer and distributed reaction zone was found during the operation in Flameless mode, the temperature profile was more uniform, and given the use of regenerative honeycombs the efficiency of the system was higher.

Acknowledgement

We gratefully acknowledge the financial support provided by the University of Antioquia through the Sostenibilidad program, and Colciencias.

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